# Attività di analisi a Bologna

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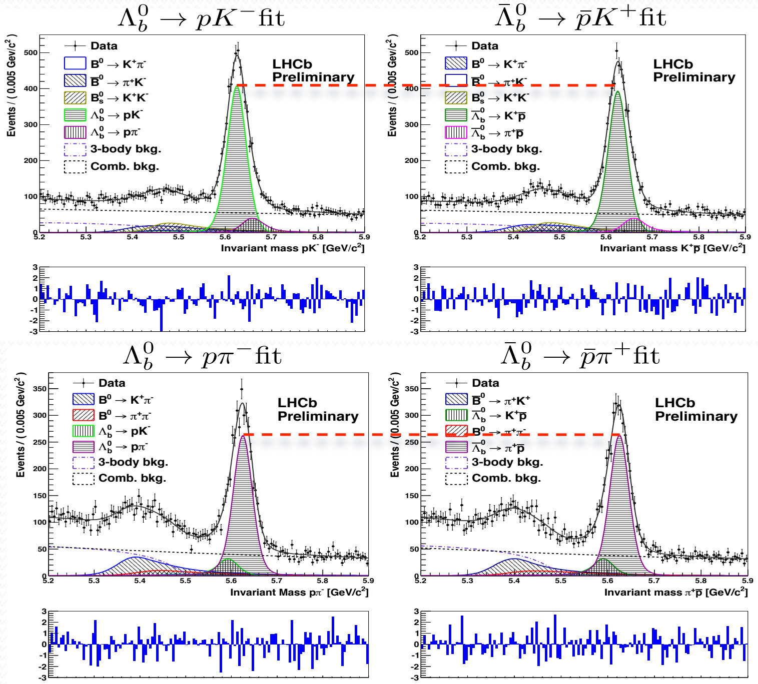
# Papers - Work in progress

- Search for CP violation in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays
  - Hadronic production asymmetries ($B^0$, $B_s^0$, $B^+$ and $\Lambda_b^0$) – nearly finished
- CP violation measurement in time-integrated $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay rates ($\Delta A_{CP}$) – finishing WG review
  - $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ – to be started
- CP violation measurement in time-dependent $B \to hh$ decays – to be started
- Search for rare decay $B^0 \to K^+K^-$ – starting review
- $D^0$ production asymmetry – nearly finished

# Search for CP violation in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays

# Introduction




- $\Lambda_b^0$ production asymmetry is a fundamental ingredient to measure CP violation in $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ decays:

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = A_{raw}(\Lambda_b^0 \to p\pi^-) + A_P(\Lambda_b^0) + A_D(p) + A_D(\pi)$$

$$A_{CP}(\Lambda_b^0 \to pK^-) = A_{raw}(\Lambda_b^0 \to pK^-) + A_P(\Lambda_b^0) + A_D(p) + A_D(K)$$

  - The raw asymmetries are

$$A_{raw}(\Lambda_b^0 \to p\pi^-) = -0.002 \pm 0.016 \text{ (stat.)}$$

$$A_{raw}(\Lambda_b^0 \to pK^-) = +0.018 \pm 0.013 \text{ (stat.)}$$

  - Need also to measure proton detection asymmetry
- Since b and $\bar{b}$ quarks are produced in pairs, measure $A_P(\Lambda_b^0)$ using the relation:

$$A_P(\Lambda_b^0) = -\left[\frac{f_d}{f_{\Lambda_b^0}} A_P(B^0) + \frac{f_u}{f_{\Lambda_b^0}} A_P(B^+) + \frac{f_s}{f_{\Lambda_b^0}} A_P(B_s^0)\right]$$

where $f_i$ are the hadronization fractions.

**This is strictly true if one includes all b mesons and baryons in the sum. We neglect $B_c$ mesons and other baryons since their contributions are negligible**

- Need to measure $A_P(B^0)$, $A_P(B_s^0)$ and $A_P(B^+)$ to obtain $A_P(\Lambda_b^0)$

# $A_P(B^0)$ and $A_P(B_s^0)$

- The following decays have been used:
  - $B^0 \to J/\psi(\mu\mu)K^{*0}$ (3 $fb^{-1}$)
  - $B_s^0 \to D_s^-(KK\pi)\pi^+$ (3 $fb^{-1}$)
- The time-dependent decay rate asymmetry is:

$$A(t) = \frac{\mathcal{R}(B(t) \to \bar{f}) - \mathcal{R}(B(t) \to f)}{\mathcal{R}(B(t) \to \bar{f}) + \mathcal{R}(B(t) \to f)} \simeq A_{CP} + A_D + A_P \frac{\cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)} t}{2}\right)}$$

Asymmetries $\lesssim 1\%$ so we retain only first order terms

Direct CP asymmetry

Final state detection asymmetry

Oscillatory term whose amplitude is the production asymmetry

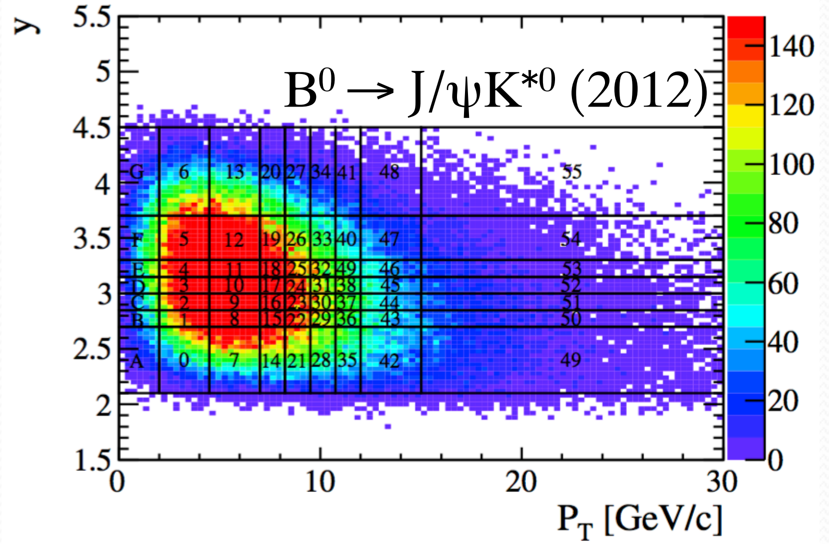
where B(t) stands for $B^0_{(s)}$ or $\overline{B}^0_{(s)}$

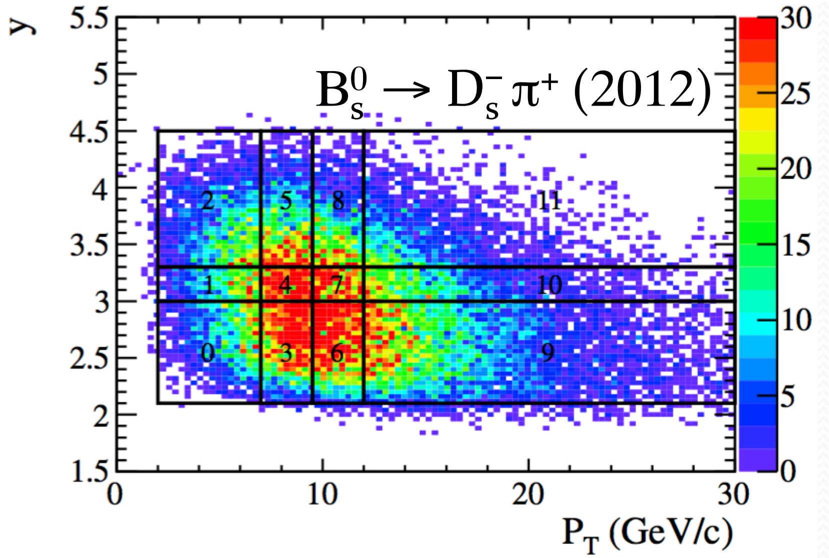
- The flavour of the meson oscillates between $B^0_{(s)}$ or $\overline{B}^0_{(s)}$ states

- Measuring A(t) one can extract $A_P$ as the **amplitude of the oscillatory term**
- Untagged time-dependent analysis

# Analysis strategy

- Divide the data sample in bins of $p_T$ and y
  - Different binning schemes for the 2 decays
  - Same binning for 2011 and 2012
  - Finer binning defined in a way to be a sub-sample of the coarser binning
- Perform 2-D simultaneous invariant mass and decay time fits for each bin
  - Integrate $A_P$ over a all bins to obtain the final integrated result
  - Integrate $A_P$ over $p_T$ or y to obtain the dependence w.r.t. the other variable



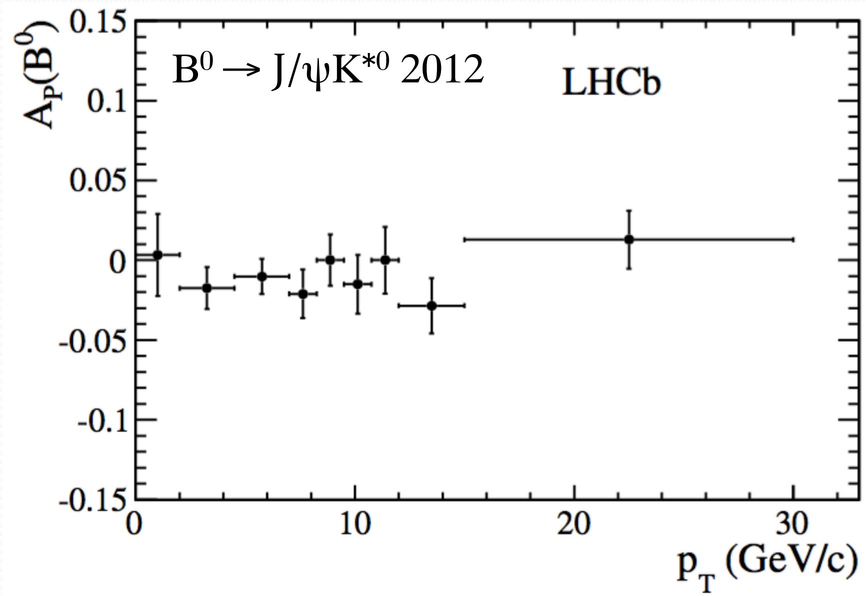



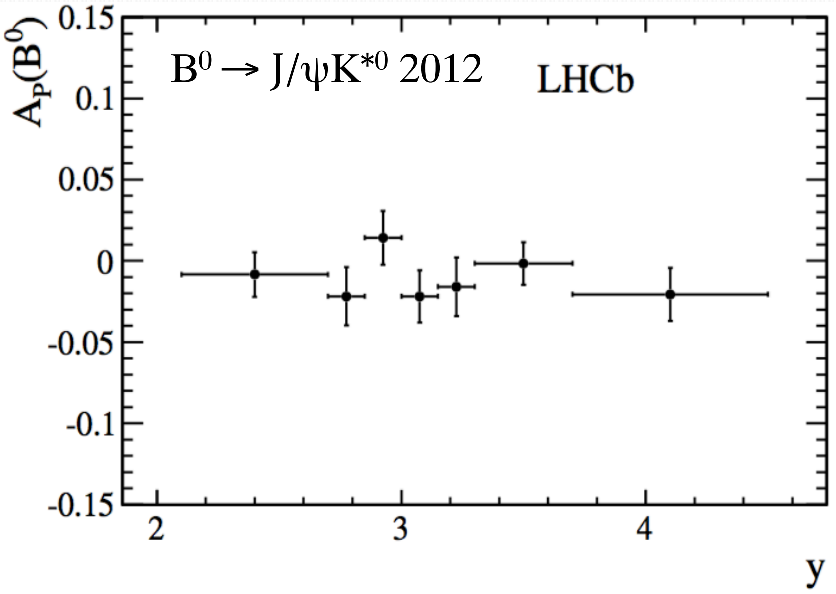
# Results

- We measured $A_P(B^0)$ in the range $0 < p_T < 30$ GeV/c and $2.1 < y < 4.5$ and $A_P(B_s^0)$ in the range $2 < p_T < 30$ GeV/c and $2.1 < y < 4.5$:

$$A_P(B^0)\ (2011) = 0.0051 \pm 0.0090\ (\text{stat.}) \pm 0.0049\ (\text{syst.})$$
$$A_P(B^0)\ (2012) = -0.0105 \pm 0.0060\ (\text{stat.}) \pm 0.0013\ (\text{syst.})$$
$$A_P(B_s^0)\ (2011) = -0.0111 \pm 0.0288\ (\text{stat.}) \pm 0.0050\ (\text{syst.})$$
$$A_P(B_s^0)\ (2012) = 0.0178 \pm 0.0196\ (\text{stat.}) \pm 0.0053\ (\text{syst.})$$

- Still need to evaluate some systematic errors on $A_P(B_s^0)$
- No evidence of a dependence of production asymmetries on $p_T$ and y with current precision




Analogous plots for 2011 $B^0$ and 2011−2012 $B_s^0$

# $A_P(B^+)$

- The following decay has been used:
  - $B^+ \to J/\psi(\mu\mu)K^+$ (3 $fb^{-1}$)
- The production asymmetry as a function of $p_T$ and y can be expressed as:

$$A_P^i(B^+) = A_{raw}^i(B^+) - A_D^i(K^+) - A_{CP}(B^+ \to J/\psi K^+)$$

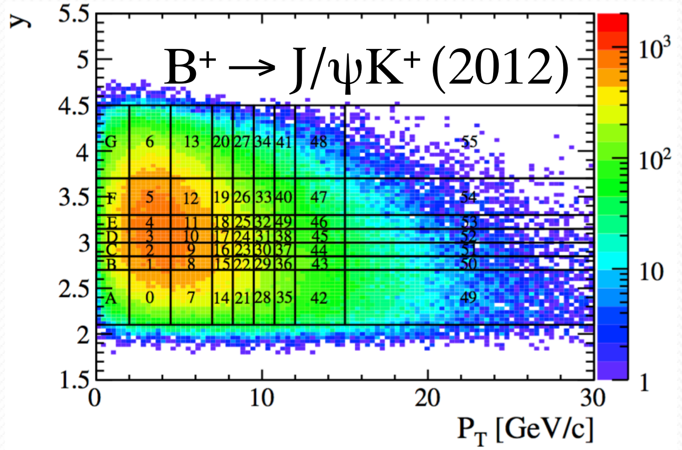
$$A_{raw}^i(B^+) = \frac{N^i(B^-) - N^i(B^+)}{N^i(B^-) + N^i(B^+)}$$

Obtained performing binned maximum likelihood fits to the invariant mass spectrum of each bin

Kaon detection asymmetry (see next slide)

Value taken from PDG (or upcoming LHCb measurement)

where *i* runs over the $(p_T, y)$ $B^+$ bins.



# Kaon detection asymmetry

- Kaon detection asymmetry depends on kaon momentum
- We use $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ decays:

$$A_{\rm raw}(K^-\pi^+\pi^+) = A_{\rm P}(D) + A_{\rm D}(K^+\pi^-) + A_D(\pi^+)$$

$$A_{\rm raw}(\overline{K}^0\pi^+) = A_{\rm P}(D) + A_{\rm D}(\pi^+) + A_{\rm D}(K^0)$$

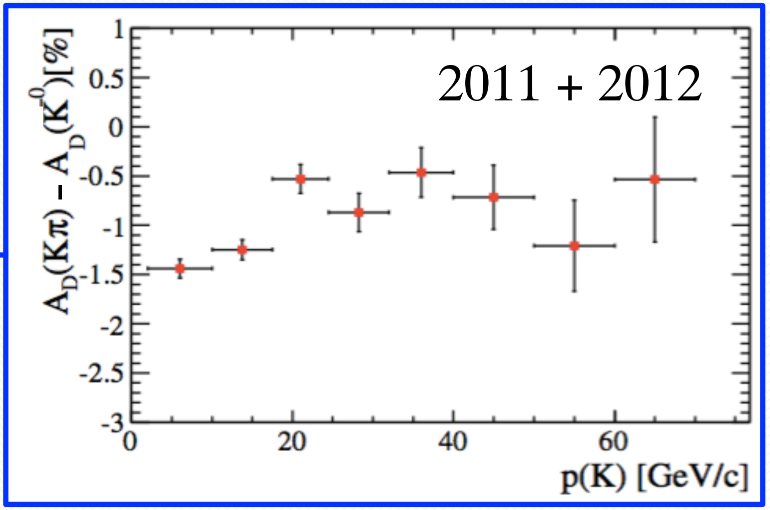
Take difference of the two above equations

$A_D(K^0) = + 0.054 \pm 0.014$ ← LHCb-ANA-2013-055

$$A_D(K^-\pi^+) - A_D(K^0) = A_{raw}(K^-\pi^+\pi^+) - A_{raw}(\bar{K}^0\pi^+)$$

- Reweighting procedure to have perfect cancellation of $A_P$ (D) and $A_D(\pi^+)$
- Measure above quantity in bins of kaon momentum:

$$A_D^i(K^+) = \sum_{j=1}^{N_{bins}^{K^+}} f_{i,j} A_D^j(K^-\pi^+) - A_D(K^0)$$




Detection asymmetry reweighted in each $B^+$ bin according to the $K^+$ momentum
$f_{i,j}$ → Fraction of events in each *j-th* $K^+$ momentum bin, calculated for every *i-th* $B^+$ $p_T$ and y bin

# Possible measurement of $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$

- Using $D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ and $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ decays, one can write the following relations:

$$A_{raw}(KK/\pi\pi) = A_{CP}(KK/\pi\pi) + A_D(D^*) + A_D(\pi_s)$$

$$A_{raw}(K\pi) = \underbrace{A_{CP}(K\pi)}_{\approx 0} + A_D(D^*) + A_D(\pi_s) + A_D(K\pi)$$

- Subtracting the two raw asymmetries one obtains:

$$A_{CP}(KK/\pi\pi) = A_{raw}(KK/\pi\pi) - A_{raw}(K\pi) + A_D(K\pi)$$

- We can correct for $A_D$ $(K\pi)$ using the measurement we already employed for

  $B^+$ production asymmetry

- First estimate : $A_{CP}(KK)$ = (x.xx ± 0.09)%, $A_{CP}(\pi\pi)$ = (x.xx ± 0.16)%

# Results

LHCb-ANA-2015−030

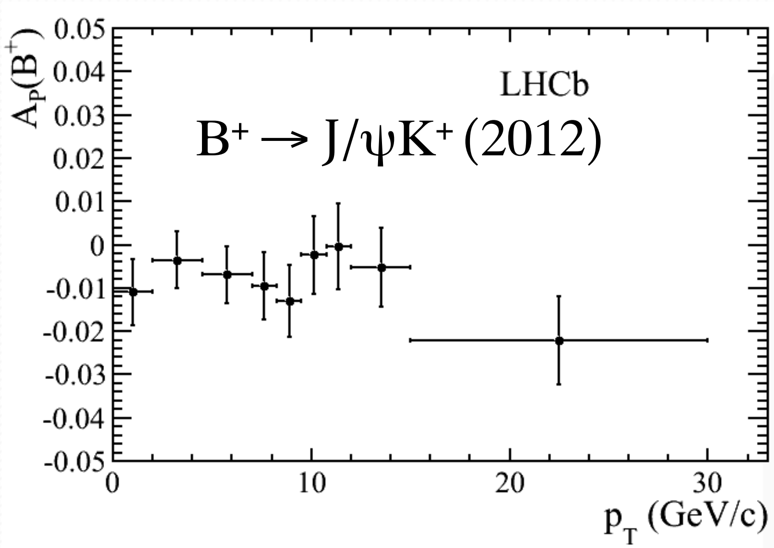
±0.0031 (stat.) ±0.0017 (syst.)

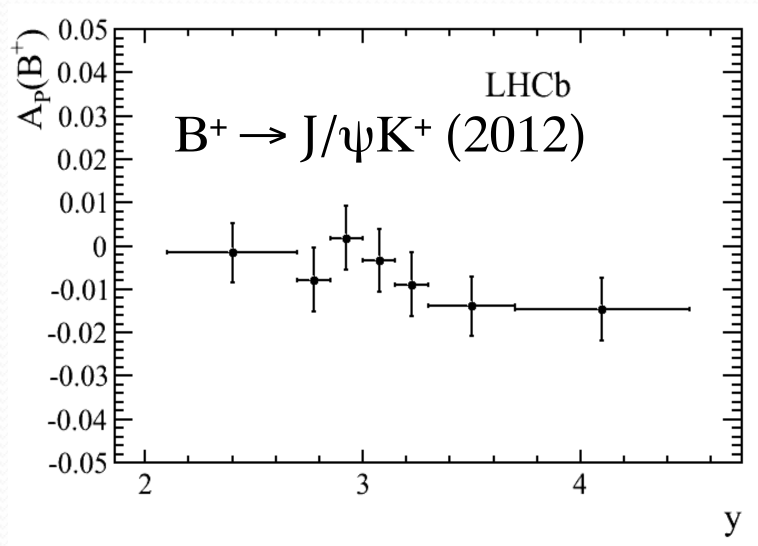
- We measured $A_P(B^0)$ in the range $0 < p_T < 30$ GeV/c and $2.1 < y < 4.5$:

  $A_P(B^+)$ (2011) = -0.0059 ± 0.0023 (stat.) ± 0.0015 (syst.) ± 0.0060 ($A_{CP}$)

  $A_P(B^+)$ (2012) = -0.0064 ± 0.0015 (stat.) ± 0.0008 (syst.) ± 0.0060 ($A_{CP}$)

- No evidence of a dependence of production asymmetries on $p_T$ and y with current precision




Analogous plots for 2011 $B^+$

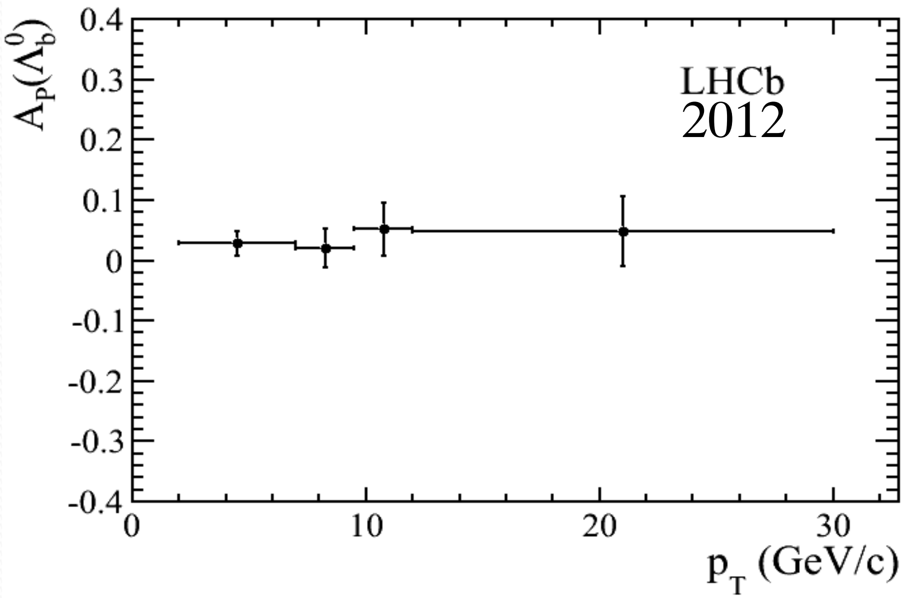
# $\Lambda_b^0$ production asymmetry results

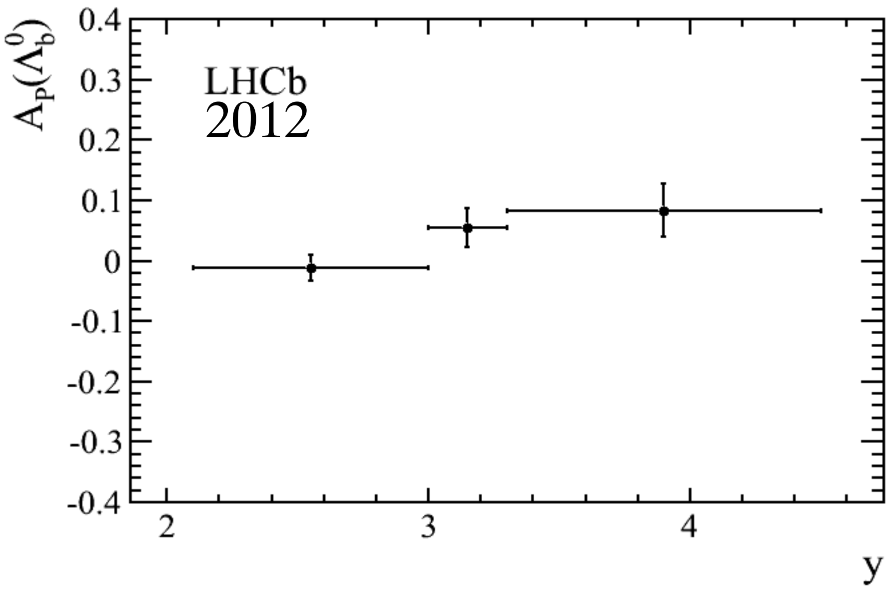
- Using the $B^0$, $B_s^0$ and $B^+$ production asymmetries measurements just presented, we obtain:

$$A_P(\Lambda_b^0)\ (2011) = 0.0319 \pm 0.0227\ (\text{stat.}) \pm 0.0072\ (\text{syst.}) \pm 0.0060\ (A_{CP}(B^+ \to J/\psi K^+))$$

$$A_P(\Lambda_b^0)\ (2012) = 0.0337 \pm 0.0148\ (\text{stat.}) \pm 0.0053\ (\text{syst.}) \pm 0.0060\ (A_{CP}(B^+ \to J/\psi K^+))$$

- Still need to evaluate some systematics uncertainties
- No evidence of a dependence of production asymmetries on $p_T$ and y with current precision




Analogous plots for 2011

# CP violation measurement in time-integrated $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay rates

# Experimental status

- Current world averages are:

$$A_{CP}(KK) = (-0.15 \pm 0.11)\%$$

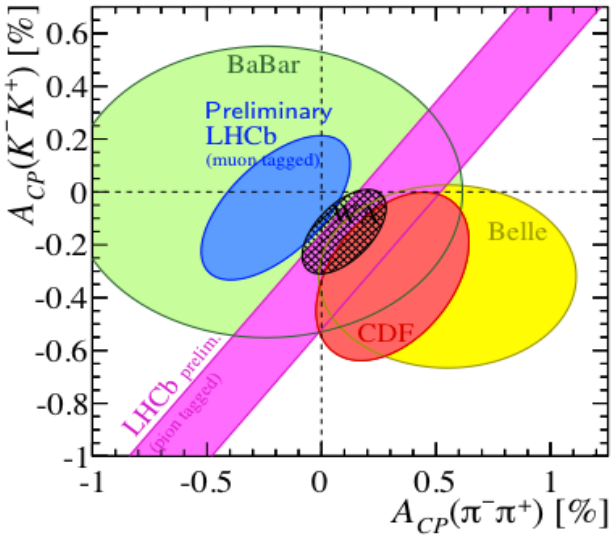
$$A_{CP}(\pi\pi) = (+0.10 \pm 0.12)\%$$

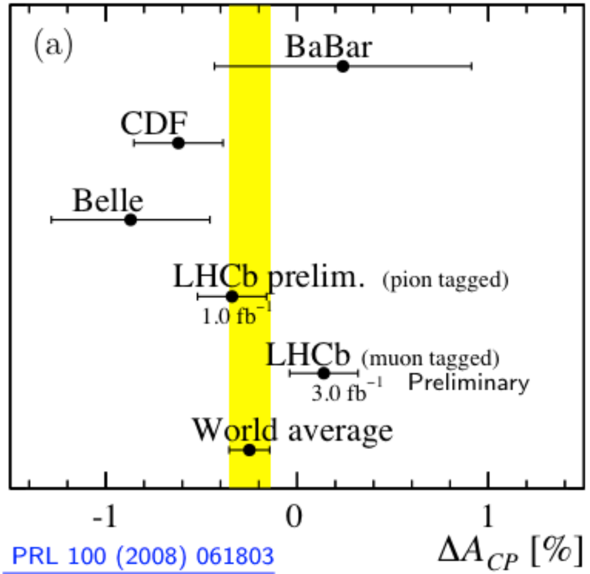
$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.15 \pm 0.11)\%$$

- This analysis will have a precision comparable with the world average of $\Delta A_{CP}$

| Experiment | $\Delta A_{CP}$ |
|---|---|
| CDF | $(-0.62 \pm 0.21 \pm 0.10)\%$ |
| BaBar | $(+0.24 \pm 0.62 \pm 0.26)\%$ |
| Belle | $(-0.87 \pm 0.41 \pm 0.06)\%$ |
| LHCb (0.6 $fb^{-1}$)[1] | $(-0.82 \pm 0.21 \pm 0.11)\%$ |
| LHCb (1.0 $fb^{-1}$)[1] | $(-0.34 \pm 0.15 \pm 0.10)\%$ |
| LHCb (3.0 $fb^{-1}$)[2] | $(+0.14 \pm 0.16 \pm 0.08)\%$ |

[1] pion-tagged
[2] muon-tagged




PRL 100 (2008) 061803
PRL 109 (2012) 111801
arXiv:1212.1975
LHCb-CONF-2013-003

# $\Delta A_{CP}$ definition

- The raw asymmetry contains **several terms** in addition to the physical asymmetry

$$A_{raw}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s) + A_P(D^*)$$

CP asymmetry — Symmetric final states — Soft pion detection asymmetry — $D^*$ production asymmetry

- Taking the difference between raw asymmetries

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

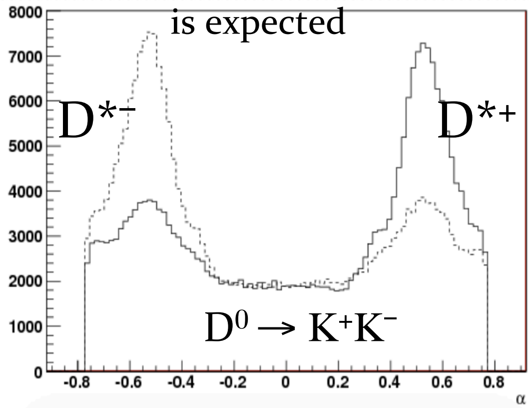
where the $D^*$ production asymmetry and the slow pion detection asymmetry **cancel out**

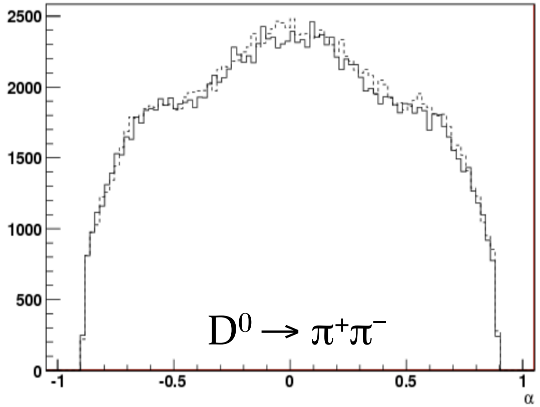
# The $\Delta A_{bkg}$ saga

- Analysis essentially at the end of review (February 2015), but…
- … checks on difference of background raw asymmetries in $\delta m$ lead to further investigation
  - Baseline analysis: $\Delta A_{bkg} = A_{bkg}(KK) - A_{bkg}(\pi\pi) = (-0.455 \pm 0.130)\% \rightarrow$ **3.4σ from zero**
  - This result could indicate a non perfect cancellation of detection asymmetries
- Effect due to the nature of background
  - **Combinatorial background ($D^0$ + random $\pi$)**: different $\pi$ reconstruction efficiencies when associated with $D^0 \rightarrow K^+K^-$ or $D^0 \rightarrow \pi^+\pi^-$ decays
  - **Physical background**: if one of the $D^0$ daughters is mis-identified, one expects an additional detection asymmetry due to the asymmetric $D^0$ final state

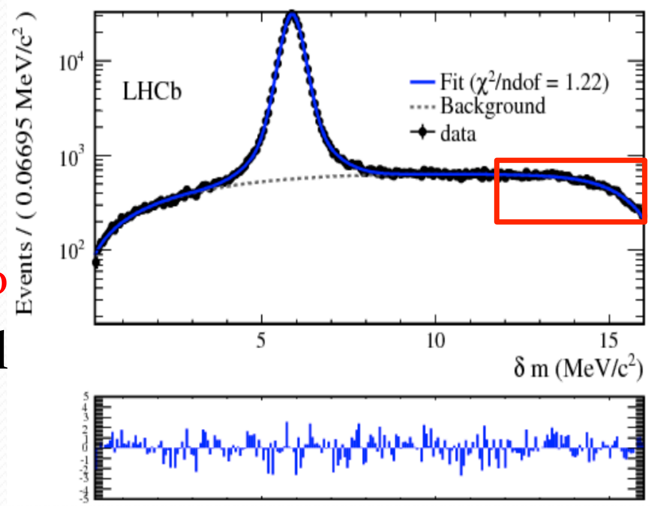
# The $\Delta A_{bkg}$ solution

1900 < m($D^0$) MeV/c² < 1915
Only combinatorial background is expected




- Increase precision on $\Delta A_{bkg}$ measurement
  - Extend $\delta m = m(D^*) - m(D^0) - m(\pi)$ fitting range from 12 to 16 MeV/c²
  - $\Delta A_{bkg} = (-0.272 \pm 0.107)\%$ → 2.7σ from zero

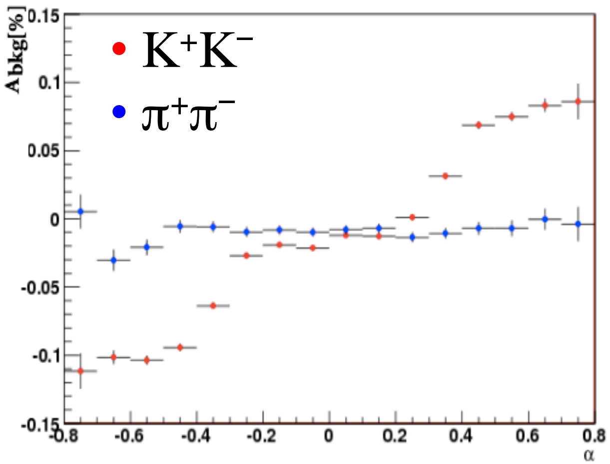



- Investigate the presence of mis-ID physical background
  - Define daughters momentum asymmetry

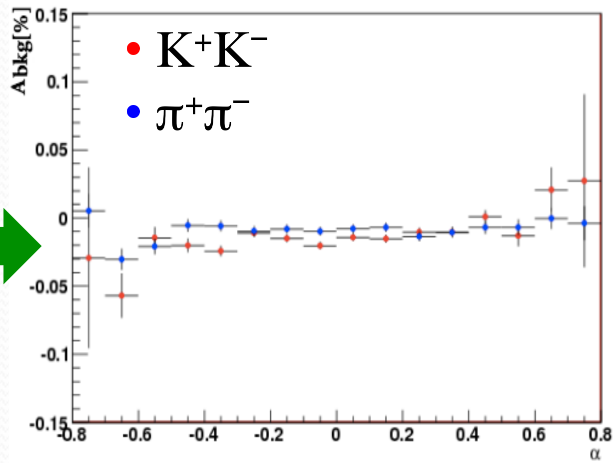
$$\alpha = [p(h^-) - p(h^+)]/[p(h^-) + p(h^+)]$$

  - Only one particle type in final state (KK, ππ): α simmetric around 0
  - Different particles in final state: α not simmetric around 0
- Large asymmetry only in $D^0 \to K^+K^-$
  - Presence of one or more mis-ID background

- Solution: apply tighter PID cuts to $K^+K^-$ candidates
- $\Delta A_{bkg} = (-0.222 \pm 0.130)\%$ → 1.7σ from zero




Tighter cuts



# Summary

- $\Delta A_{bkg}$ is now 1.7σ from zero
- $\Delta A_{CP}$ value **stable** indipendently of different δm ranges and tighter PID cuts

| | $\Delta A_{\rm bkg}$ [%] | $\Delta A_{\rm CP}$ [%] |
|---|---|---|
| Baseline | $-0.445 \pm 0.130$ | $0.276 \pm 0.078$ |
| $\delta m \in [0.2 - 16]$ MeV/$c^2$ | $-0.272 \pm 0.107$ | $0.257 \pm 0.078$ |
| $\delta m \in [12 - 16]$ MeV/$c^2$ | $0.096 \pm 0.189$ | – |
| tight PID cuts | $-0.391 \pm 0.155$ | $0.280 \pm 0.088$ |
| $\delta m \in [0.2 - 16]$ + tight PID cuts | $-0.222 \pm 0.130$ | $0.263 \pm 0.088$ |
| $\delta m \in [12 - 16]$ MeV/$c^2$ + tight PID cuts | $0.138 \pm 0.230$ | – |

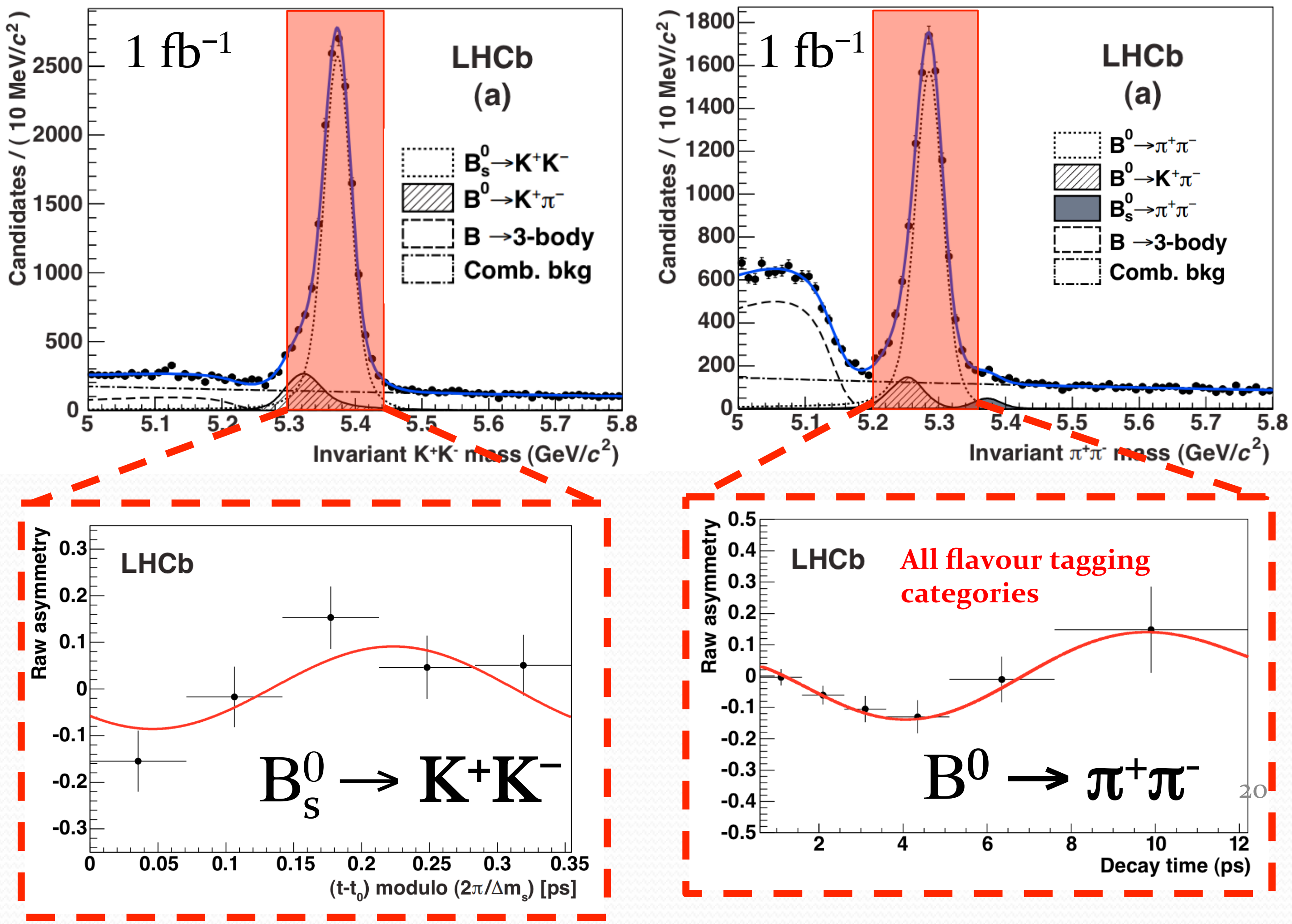
- $\Delta A_{CP}$ analysis performed with 2011 and 2012 data
  - Total statistical error is 0.08% (2011+2012)
  - Total systematic error is 0.03%
  - Most precise single measurement of CP violation in charm sector to date
  - 2012 result still **BLIND**
- Analysis close to unblinding and then approval

# CP violation measurement in time-dependent B → hh decays

# Experimental status – Time dipendent CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ decays

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$
$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$




Rsults published in JHEP 10 (2013) 183

# General observations

- Previous analysis based on 1 $fb^{-1}$
  - Expect a factor ~ x 3 in statistics using the full dataset
- Only OS taggers used
  - Run 1 effective tagging power: $\varepsilon_{eff} = (2.45 \pm 0.25)\%$
  - Expect ~ x 1.5 in $\varepsilon_{eff}$ due to SSk for $B_s^0 \rightarrow K^+K^-$ decay
  - Expect ~ x 1.5 in $\varepsilon_{eff}$ due to SSπ and SSp (new) for $B^0 \rightarrow \pi^+\pi^-$
- Fundamental points in analysis update
  - SSk calibration depends on $B_s^0 \rightarrow K^+\pi^-$ statistic
    - It is possible to use official calibrations from FT group
  - Decay time resolution → dominant systematic uncertainty in $B_s^0 \rightarrow K^+K^-$ decay

# Analysis update status

- New fit code
  - Execution time largely reduced
  - Simultaneous fit of $K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$, $K^+K^-$ spectra
  - Event by event decay time resolution and mistag-fraction
- New code is currently being validated with MC signal events
  - For now only OS, SSk, SSπ taggers
    - Will include also SSp and OS_charm

# Search for rare decay $B^0 \rightarrow K^+K^-$

# Motivations

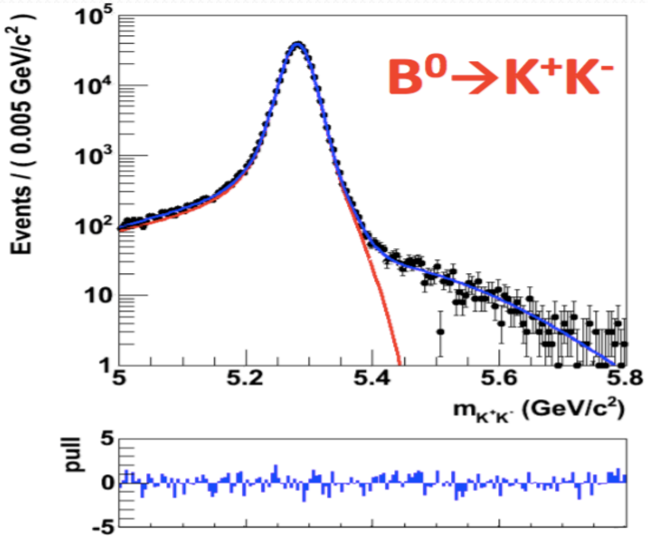
- The $B^0 \to K^+ K^-$ decay is still unobserved
- The $B^0 \to K^+ K^-$ decay is governed by pure penguin annihilation topologies
  - Good probe for NP effects
- Expected BR ~ $10^{-7} - 10^{-8}$

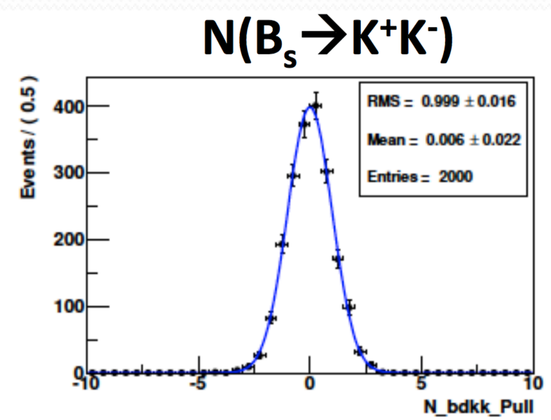
| BR x $10^{-6}$ | | | | |
|---|---|---|---|---|
| BaBar | Belle | CDF | LHCb | HFAG |
| $0.04 \pm 0.15 \pm 0.08$ | $0.10 \pm 0.08 \pm 0.04$ | $0.23 \pm 0.10 \pm 0.10$ | $0.11^{+0.05}_{-0.04} \pm 0.06$ | $0.12 \pm 0.05$ |

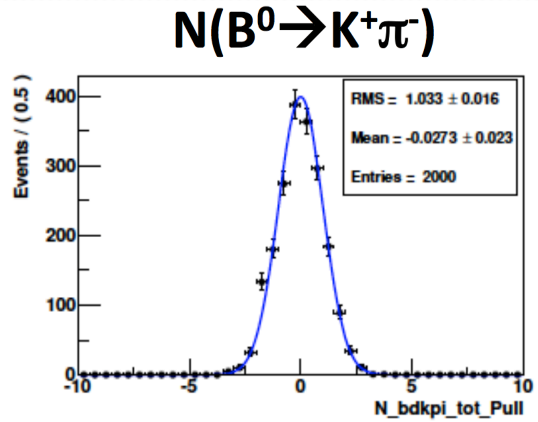
- **BLIND** analysis

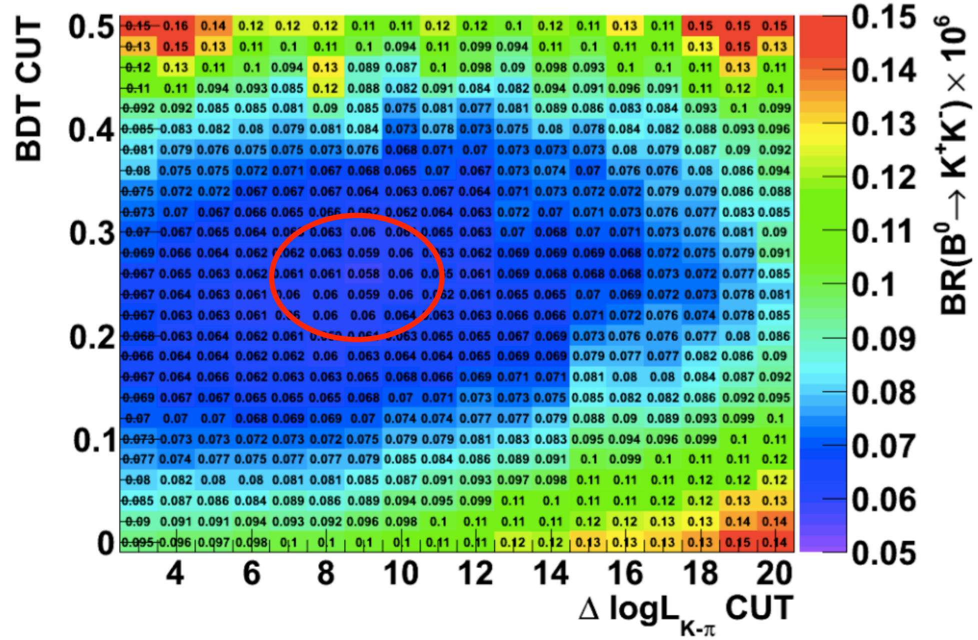
# Analysis status

- Invariant mass model and other components already studied
- Event selection has been optimized
  - Find set of cuts (BDT+ΔlogL) giving a **5σ significance** on the smallest BR($B^0 \rightarrow K^+ K^-$)
- Final fit of all $H_b \rightarrow h^- h'^+$ spectra has been validated using fast MC toys
  - Pulls of relevant variables do not show problems



# Conclusions

- Analysis is in an advanced status and major problems have been adressed
- Main sources of systematic uncertainties have been identified and studied
  - Parametrization of radiative tail
  - Combinatorial background model
  - PID calibration
  - Model of cross-feed background
  - Model of 3-body partially reconstructed background
- Analysis ready to go to review

# $D^0$ production asymmetry

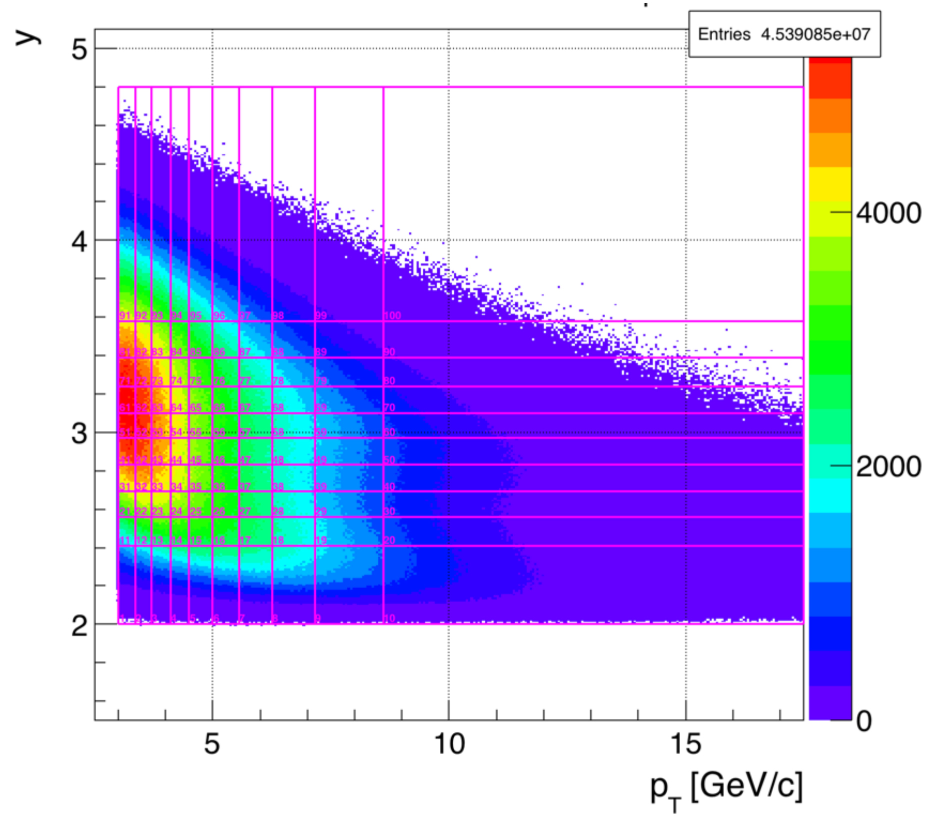
# $D^0$ production asymmetry: strategy

- We reconstruct prompt $D^0$ decaying into $K^+\pi^-$ final state.
- We can write the raw asymmetry as:

$$A_{\mathrm{raw}}(K\pi) = A_D(K\pi) + A_P(D^0)$$

Extracted from the invariant mass fits

Same as for $B^+$ production asymmetry

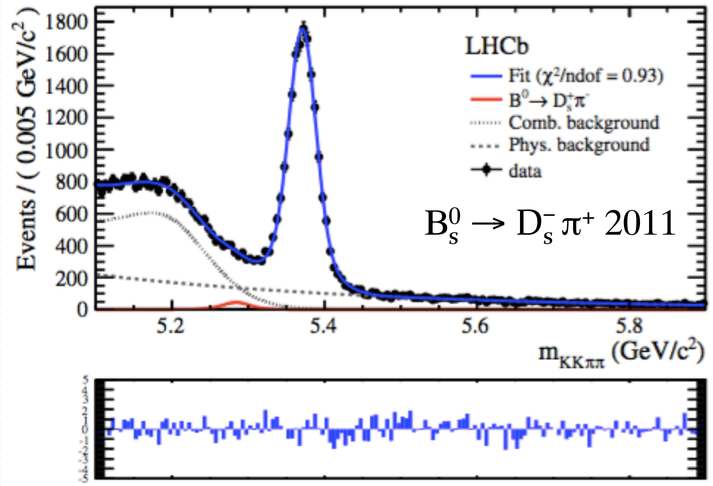



- Big statistics allow to have finer binning (10x10) w.r.t. B mesons production asymmetry measurements
- Analysis nearly ended

# Backup slides

# Data sample and event selection

- We used the full 2011 and 2012 data sample collected by the LHCb detector
- PID requirements to suppress background due to mis-ID of final state particles
- Multivariate analysis (BDT) to suppress combinatorial background
- From maximum likelihood fits we obtain:




| Parameter | $B^0 \to J/\psi K^{*0}$ (2011) | $B^0 \to J/\psi K^{*0}$ (2012) | $B^0_s \to D^-_s \pi^+$ (2011) | $B^0_s \to D^-_s \pi^+$ (2012) |
|---|---|---|---|---|
| $N^{sig}$ | $95\,081 \pm 369$ | $225\,302 \pm 825$ | $16\,933 \pm 174$ | $36\,277 \pm 245$ |
| $N^{comb}$ | $26\,972 \pm 260$ | $69\,126 \pm 723$ | $14\,930 \pm 432$ | $21\,399 \pm 676$ |
| $N^{phys}_{B^0{}_{(s)} \to D^-{}_{(s)} \rho^+}$ | – | – | $3\,703 \pm 435$ | $7952 \pm 626$ |
| $N^{phys}_{B^0{}_{(s)} \to D^{*-}{}_{(s)} \pi^+}$ | – | – | $15\,149 \pm 572$ | $29\,239 \pm 830$ |